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TRIANNUAL REPORT

on the

DESIGN, ANALYSIS, AND TEST VERIFICATION OF ADVANCED ENCAPSULATION SYSTEMS

For Period Ending

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The JPL Low-Cost Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE.

TABLE OF CONTENTS

Section 1.0

SUMMARY STATEMENT

The construction of optical and electrical verification test coupons is detailed. Testing of these coupons was completed and the results are presented. Additionally, a thermal simulation of roof mounted array conditions was done and the results documented.

Section 2.0

INTRODUCTION

The objective of this program is to develop analytical methodology for advanced encapsulation systems which will aid in the determination of optimum systems for meeting the Low Cost Solar Array Project goals. The program consists of three phases. In Phase I, analytical models were developed to perform optical, thermal, electrical, and structural analyses on candidate encapsulation systems. From these analyses a candidate system will be selected for qualification testing during Phase II.

Additionally, during Phase II, test specimens of various types will be constructed and tested to determine the validity of the analysis methodology developed in Phase I.

In Phase III, a finalized optimum design based on knowledge gained in Phases I and II will be developed and delivered to JPL.

Section 3.0

TECHNICAL DISCUSSION

3.1 Optical Testing

The optical coupons were completed and all optical testing done. Table 1 lists the construction elements of optical test samples, Figure 1 shows a typical construction. Thicknesses shown in Table 1 for the encapsulant are nominal. All samples were measured after encapsulation to determine the actual thicknesses. Table 2 shows the thickness of various layers and the determined encapsulant thicknesses. Table 3 shows data from the optical testing.

Cell #BC-11 in Sample OC-1 was severely cracked during encapsulation and Cell #B-7 in sample OC-6 had a residue on the surface prior to encapsulation. Both these cells will not be included for comparison with computer/model predicted results. This data was passed on to Hughes for comparison to predicted results.

3.2 Electrical Testing

The electrical test coupons were prepared and electrical testing completed. Table 4 shows the types of specimens that were made, Figure 2 shows the construction of a typical coupon and Figure 3, the test setup.

Approximately twenty-five samples of each type were made. Measurements of thicknesses were made on several coupons, and there was agreement with the nominal values listed in Table 4.

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Table 1

OPTICAL VERIFICATION TEST SPECIMENS

COUPON NO.	OC-1	OC-2	OC-3	OC-4	OC-5	OC-6	OC-7	OC-8	OC-9	OC-10	OC-11	OC-12	OC-13
Load Bearing Member	Low-Iron Glass Stipple-In	Low-Iron Glass Stipple-In	High-Iron Glass	Low-Iron Glass Stipple-In	Low Iron Glass Stipple-Out	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Top Cover	--	--	--	--	--	Korad	Tedlar	Tedlar	Tedlar	Tedlar	Tedlar	Tedlar	Tedlar
Encapsulant	EVA	EVA	EVA	EVA/CG	EVA/CG	EVA	EVA	EVA/CG	EVA/CG	EVA/CG	EVA	EVA	EVA/CG
Encapsulant Thickness	10 mil	10 mil	10 mil	10 mil	10 mil	10 mil	10 mil	10 mil	10 mil	10 mil	54 mil	10 mil	10-mil
Cell Type*	SC-2"Sq	PC-2"x4"	SC-2"Sq	SC-2"Sq	SC-2"Sq	SC-2"Sq	SC-2"Sq	SC-2"Sq	SC-2"Sq (AR)	SC-2"D (Text)	SC-2"Sq	SC-2"Sq (AR)	SC-2"D (AR-Text)
No. Cells	2	2	2	2	2	2	2	2	2	2	2	2	2

*SC - Single Crystal Silicon
PC - Polycrystalline Silicon

N/A - Not applicable for this test

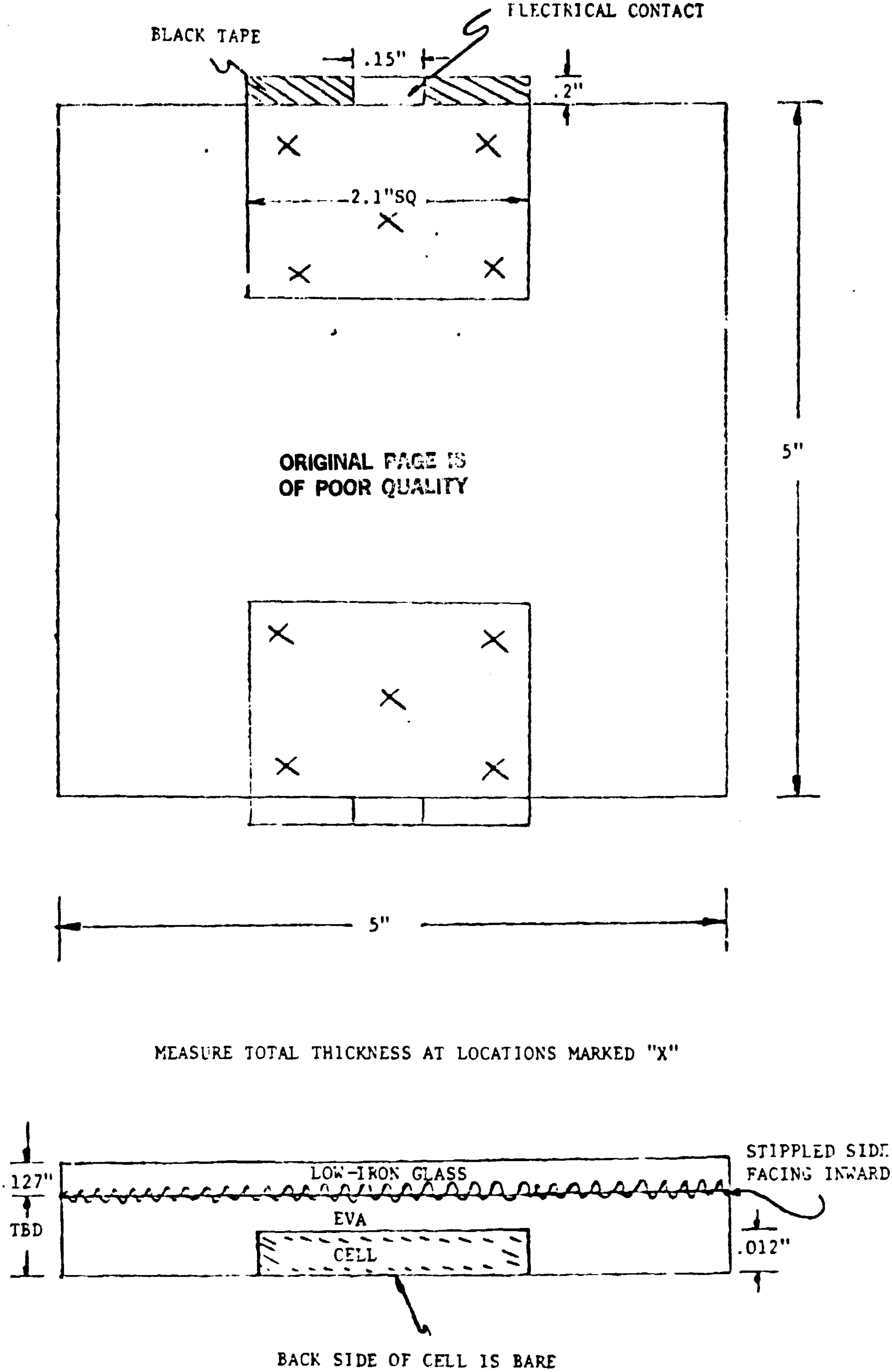

Figure 1. TYPICAL OPTICAL TEST COUPON

Table 2

COUPON THICKNESS

		Cell Thickness	Glass	Tedlar	Korad	Sample Thick.	Encap. Thick.
OC-1	BC-11	.012	.138	-	-	159	9
	BC-15	.012	.138	-	-	162	12
OC-2	A	.018	.131	-	-	156	7
	AA	.018	.131	-	-	155	6
OC-3	BC-14	.012	.119	-	-	147	16
	BC-9	.012	.119	-	-	143	12
OC-4	BC-17	.012	.128	-	-	154	14
	BC-18	.012	.128	-	-	154	12
OC-5	BC-10	.012	.127	-	-	162	23
	BC-13	.012	.127	-	-	160	21
OC-6	I-16	.012	-	-	.003	33	18
	BC-7	.012	-	-	.003	32	17
OC-7	I-17	.012	-	.004	-	34	18
	I-18	.012	-	.004	-	34	18
OC-8	I-7	.012	-	.004	-	35	19
	I-6	.012	-	.004	-	34	18
OC-9	B-5	.012	-	.004	-	35	19
	B-14	.013	-	.004	-	35	18
OC-10	B-15	.014	-	.004	-	37	19
	B-16	.014	-	.004	-	34	16
OC-11	± -4	.012	-	.004	-	72	56
	± 12	.012	-	.004	-	70	54
OC-12	B-18	.013	-	.004	-	34	17
	B-19	.013	-	.004	-	35	18
OC-13	B-23	.014	-	.004	-	38	10
	B-24	.014	-	.004	-	41	13

Table 3. DATA FROM OPTICAL TESTING

		Xenon Light Source					Tungsten Light Source				
Sample	Cell #	V_{oc} Before/ After	I_{sc} Before/ After	I_{500} Before/ After	I_{sc} Ratio A/B	I_{500} Ratio A/B	V_{oc} Before/ After	I_{sc} Before/ After	I_{500} Before/ After	I_{sc} Ratio A/B	I_{500} Ratio A/B
OC-1	BC-11	595/598	635/768	561/468	1.21	.83	585/584	521/721	450/420	1.38	.93
	BC-15	596/598	618/805	577/715	1.31	1.24	586/588	514/756	454/653	1.47	1.44
OC-2	A	536/540	952/1160	506/649	1.22	1.28	530/530	787/952	367/455	1.21	1.24
	AA	539/547	862/1080	464/651	1.25	1.40	533/535	726/866	345/439	1.19	1.27
OC-3	BC-14	597/594	647/732	536/646	1.13	1.21	587/571	527/648	469/526	1.23	1.12
	BC-9	597/597	634/733	577/656	1.16	1.14	587/576	524/650	466/546	1.24	1.17
OC-4	BC-17	598/596	634/837	577/750	1.32	1.30	587/590	529/760	472/669	1.44	1.42
	BC-18	594/595	647/830	536/658	1.28	1.23	583/582	529/762	431/585	1.44	1.36
OC-5	BC-10	597/597	637/829	574/737	1.30	1.28	587/583	520/774	460/661	1.49	1.44
	BC-13	597/595	622/815	564/730	1.31	1.29	586/583	523/761	464/668	1.46	1.44
OC-6	I-16	591/593	632/779	550/674	1.23	1.23	582/585	592/714	502/605	1.21	1.21
	B-7	597/602	669/737	603/765	1.10	1.27	597/596	649/694	577/594	1.07	1.03
OC-7	I-17	592/592	619/755	552/650	1.22	1.18	580/588	529/716	440/613	1.35	1.39
	I-18	591/591	625/765	553/643	1.22	1.16	579/584	529/721	435/591	1.36	1.36
OC-8	I-7	590/592	622/759	508/674	1.22	1.33	578/585	507/722	446/619	1.42	1.39
	I-6	592/595	619/762	556/674	1.23	1.21	578/587	517/727	435/610	1.41	1.40
OC-9	B-5	602/597	857/853	762/748	1.00	.98	593/587	788/796	692/665	1.01	.96
	B-14	603/598	857/852	780/784	.99	1.01	594/588	784/797	705/689	1.02	.98
OC-10	#15	590/590	701/737	578/597	1.05	1.03	580/582	642/673	511/534	1.05	1.05
	#16	580/587	703/740	569/581	1.05	1.02	578/578	644/670	503/512	1.04	1.02
OC-11	I-4	591/594	614/766	511/682	1.25	1.24	579/585	510/731	441/638	1.43	1.45
	I-12	590/591	618/754	542/658	1.22	1.21	578/583	504/715	423/622	1.42	1.47
OC-12	B-18	602/596	863/806	786/717	.93	.91	594/582	789/762	710/652	.97	.92
	B-19	602/596	857/815	770/718	.95	.93	594/584	781/765	694/648	.98	.93
OC-13	#23	589/589	756/739	570/552	.98	.97	581/571	696/681	505/465	.98	.92
	#24	595/592	751/742	609/571	.99	.94	589/578	693/684	550/489	.99	.89

Table 4

SPECIMENS FOR ELECTRICAL VERIFICATION TESTS

Type	Front Side		Back Side	
A	.004 Tedlar	.018" EVA/CG	.018" EVA/CG	.001 Al/Polyester
B	.001 Tedlar	.018" EVA/CG	.036" EVA/CG	.001 Al/Polyester
C	.001 Tedlar	.018" EVA	.018" EVA/CG	Wood*
D	.001 Tedlar	.036" EVA/CG	.036" EVA/CG	Wood*

*Duron (U. S. Gypsum Co.)

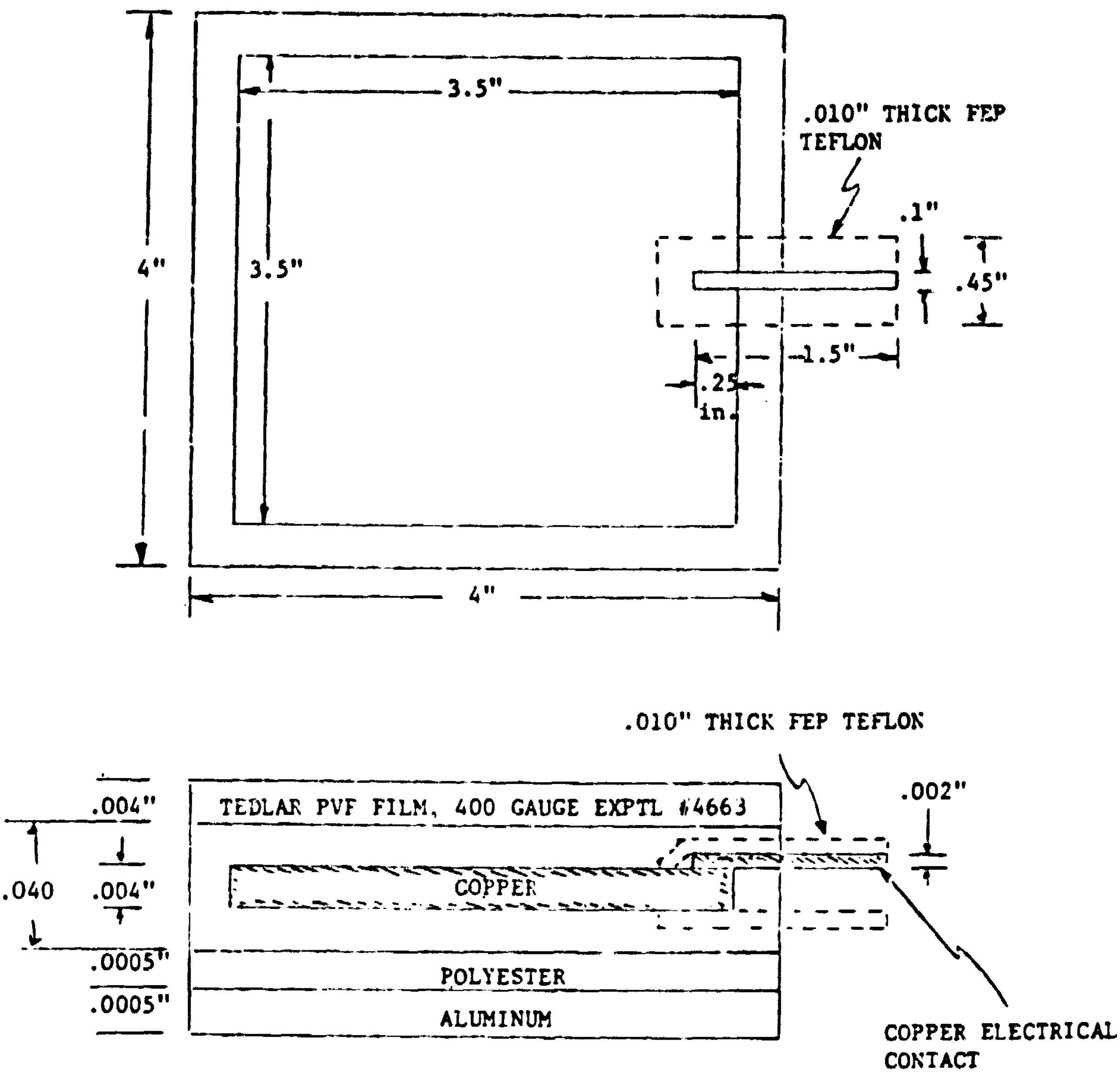

Figure 2. ELECTRICAL COUPON, TYPE A

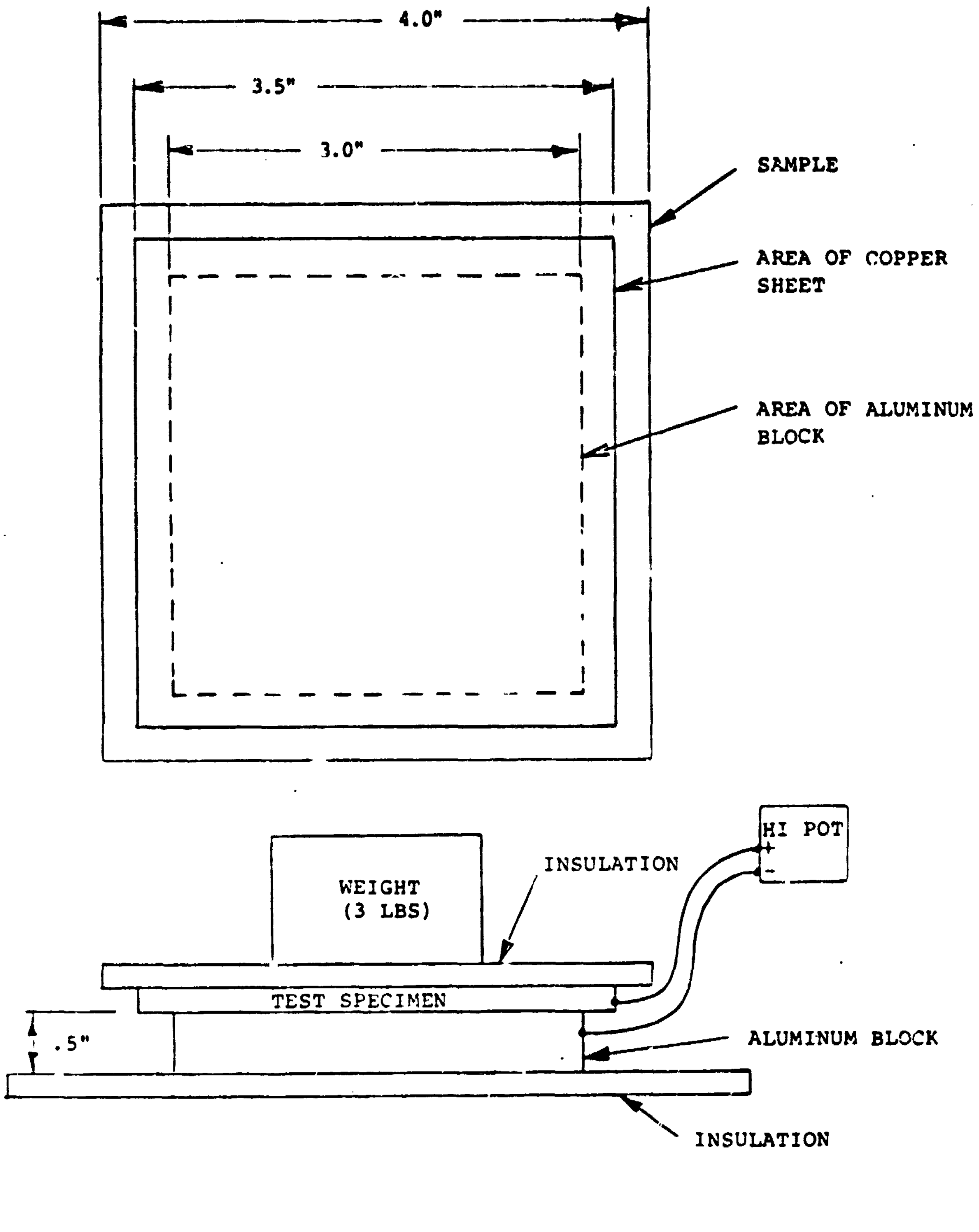

Figure 3. SETUP FOR ELECTRICAL ISOLATION TESTS

Due to technician error 10 of the D type samples had no Craneglas on the front side. This change breaks the test into 9 groups of data instead of 8; A front, A back, B front, B Back, C front, C back, D front, D back, and D front no Craneglas. Tables 5-13 report the data from the test. The voltage at breakdown is reported in kV, breakdown is defined as more than 50 microamps leakage. In all cases it was catastrophic. The voltage at which 1 microamp leakage occurred, and then leakage just before breakdown is also recorded. All voltages were direct current with the positive electrode connected to the copper sheet in the coupon which simulates the cell. Table 14 is a summary of the data. This data has been given to Hughes for comparison to the results of the electrical predictions.

3.3 Thermal/Optical Model

To approximate conditions in a roof mounted array the cell temperature of both wood and steel substrate modules were determined when there is no convective heat transfer off the back (anti sun) side of the module. These calculations were performed for modules using single crystal silicon cells with AR coating. The results are shown in Table 15.

Table 5

FRONT SIDE COUPON TYPE A

Coupon	Breakdown kV	Leakage at Breakdown μA	kV at 1 μA Leakage
F-A-1	19	10.5	3
F-A-2	18	14.5	5
F-A-3	17	32.0	3
F-A-9	14	7.5	5
F-A-10	14	10.5	4
F-A-11	15	11.0	4
F-A-12	19	20.0	4
F-A-13	12	8.0	4
F-A-14	15	19.0	4
F-A-15	19	25.0	3
F-A-16	18	22.5	4
F-A-17	10	7.0	4
F-A-18	13	27.0	3
F-A-19	17	24.0	3
F-A-20	12	22.0	3
F-A-21	10	7.0	3
F-A-22	17	23.0	4
F-A-23	16	20.0	3
F-A-24	18	31.0	4
F-A-25	17	32.0	3
F-A-26	15	23.0	3
F-A-27	17	29.0	3

$n = 22$ $\bar{x} = 15.6$ kV $s_x = 2.8$

Table 6

FRONT SIDE COUPON TYPE B

Coupon	Breakdown kV	Leakage at Breakdown μA	kV at 1 μA Leakage
F-B-1	13	30.0	2
F-B-2	12	19.5	3
F-B-3	18	44.0	2
F-B-4	14	28.0	2
F-B-5	17	35.0	3
F-B-6	15	28.0	3
F-B-7	15	28.0	2
F-B-8	15	26.0	3
F-B-9	17	31.0	2
F-B-10	15	19.0	3
F-B-11	19	24.0	4
F-B-12	15	19.0	3
F-B-13	17	20.0	4
F-B-14	15	19.0	3
F-B-15	15	21.0	3
F-B-16	15	19.0	3
F-B-17	12	17.0	2
F-B-18	17	36.0	3
F-B-19	15	39.0	2
F-B-20	13	24.0	2
F-B-21	16	35.0	3
F-B-22	13	32.0	2
F-B-23	17	45.0	2

$n = 23$ $\bar{x} = 15.2$ kV $s_x = 1.9$

Table 7

FRONT SIDE COUPON TYPE C

Coupon	Breakdown kV	Leakage at Breakdown μA	kV at 1 μA Leakage
F-C-1	14	27.0	3
F-C-2	11	21.0	3
F-C-4	15	29.0	3
F-C-5	18	40.0	3
F-C-7	16	45.0	3
F-C-8	14	37.5	3
F-C-9	15	31.0	3
F-C-10	16	35.0	3
F-C-11	17	41.0	3
F-C-12	17	43.0	3
F-C-13	12	23.0	3
F-C-14	21	43.0	3
F-C-15	16	42.0	3
F-C-16	15	29.0	4
F-C-17	15	39.0	3
F-C-18	15	41.0	3
F-C-19	6	6.0	3
F-C-20	9	17.0	3
F-C-21	9	7.8	3
F-C-22	9	9.0	3
F-C-23	11	27.0	3
F-C-24	7	6.5	3
F-C-25	12	15.0	3
F-C-26	16	27.0	3
F-C-27	5	3.8	3
F-C-28	13	23.2	3

Table 7 (continued)

Coupon	Breakdown kV	Leakage at Breakdown μA	kV at 1 μA Leakage
F-C-29	12	17.5	3
F-C-30	15	2.2	3
F-C-31	15	42.0	3
F-C-32	12	19.0	3
F-C-33	11	20.5	3

$n = 31$ $\bar{x} = 13.2$ kV $s_x = 3.6$

Table 8

FRONT SIDE COUPON TYPE D WITH CRANEGLAS

Coupon	Breakdown kV	Leakage at Breakdown μA	kV at 1 μA Leakage
F-D-13	10	1.8	7
F-D-14	18	7.5	6
F-D-15	22	18.0	7
F-D-16	21	17.0	7
F-D-17	19	19.0	6
F-D-18	17	18.0	6
F-D-19	18	10.5	6
F-D-20	15	7.0	6
F-D-21	18	11.0	6
F-D-22	23	24.0	6
F-D-23	16	9.5	6
F-D-26	22	10.2	8
F-D-27	16	3.8	10
F-D-28	21	12.5	8
F-D-29	12	3.5	8
F-D-30	21	11.0	8

$n = 16$ $\bar{x} = 18.1$ kV $s_x = 3.7$

Table 9

FRONT SIDE COUPON TYPE D WITHOUT CRANEGLAS

Coupon	Breakdown kV	Leakage at Breakdown μA	kV at 1 μA Leakage
F-D-1	14	6.0	5
F-D-2	25*	17.0	9
F-D-3	12	4.0	7
F-D-4	16	12.0	6
F-D-5	17	10.5	7
F-D-6	14	6.5	7
F-D-9	17	13.5	5
F-D-10	14	7.8	6
F-D-11	12	7.5	5
F-D-12	16	9.2	6

$n = 10$ $\bar{x} = 15.8$ kV $s_x = 4.0$

*No Breakdown (Samples with no breakdown were included at 25 kV for statistical purposes.)

Table 10

BACK SIDE COUPON TYPE A

Coupon	Breakdown kV	Leakage at Breakdown μA	kV at 1 μA Leakage
B-A-1	9	8.0	5
B-A-2	8	1.3	7
B-A-3	7	1.0	6
B-A-9	9	1.2	7
B-A-10	11	2.0	6
B-A-11	8	1.5	7
B-A-12	9	11.0	9
B-A-13	5	1.0	5
B-A-14	9	2.5	5
B-A-15	10	3.0	6
B-A-16	9	1.0	8
B-A-17	1		
B-A-18	3	2.0	3
B-A-19	6	1.5	6
B-A-20	1		
B-A-21	6	1.0	5
B-A-22	2		
B-A-23	8	1.5	5
B-A-24	8	1.8	6
B-A-25	7	1.0	6
B-A-26	2		
B-A-27	10	2.2	5

$n = 22$ $\bar{x} = 6.8$ kV $s_x = 3.1$

Table 11

BACK SIDE COUPON TYPE B

Coupon	Breakdown kV	Leakage at Breakdown μA	kV at 1 μA Leakage
B-B-1	8	1.2	6
B-B-2	5	.4	
B-B-3	9	1.3	7
B-B-4	6	.8	
B-B-5	7	.5	
B-B-6	9	1.0	8
B-B-7	7	.7	
B-B-8	9	1.0	8
B-B-9	10	1.2	8
B-B-10	9	1.0	8
B-B-11	12	1.5	9
B-B-12	8	.9	
B-B-13	7	.6	
B-B-14	8	.7	
B-B-15	9	.9	
B-B-16	12	1.5	9
B-B-17	9	.8	
B-B-18	13	1.2	10
B-B-19	7	.6	
B-B-20	10	1.2	9
B-B-21	9	.9	
B-B-22	5	.5	
B-B-23	10	1.2	8

$n = 23$ $\bar{x} = 8.6$ kV $s_x = 2.1$

Table 12

BACK SIDE COUPON TYPE C

Coupon	Breakdown kV	Leakage at Breakdown μA	kV at 1 μA Leakage
B-C-1	25	3.0	12
B-C-2	25*	6.0	15
B-C-4	25	11.0	14
B-C-5	25	10.0	13
B-C-7	23	4.0	11
B-C-8	21	4.8	12
B-C-9	21	6.5	11
B-C-10	25*	8.0	13
B-C-11	19	1.0	17
B-C-12	22	9.0	11
B-C-13	25	7.5	9
B-C-14	19	4.0	11
B-C-15	25	7.2	11
B-C-16	25	7.0	16
B-C-17	25	10.0	9
B-C-18	25	10.0	11
B-C-19	21	8.0	11
B-C-20	25	10.0	12
B-C-21	20	5.5	13
B-C-22	24	12.0	12
B-C-23	24	3.0	14
B-C-24	20	2.0	14
B-C-25	23	8.0	12
B-C-26	23	7.0	12
B-C-27	25*	8.5	12
B-C-28	25*	10.5	11

*No Breakdown (Samples with no breakdown were included at 25 kV for statistical purposes.)

Table 12 (continued)

Coupon	Breakdown kV	Leakage at Breakdown μA	kV at 1 μA Leakage
B-C-29	9	6.2	4
B-C-30	8	3.0	4
B-C-31	20	4.0	13
B-C-32	25*	10.0	10
B-C-33	23	6.7	13

$n = 32$ $\bar{x} = 22.2$ kV $s_x = 4.2$

*No Breakdown (Samples with no breakdown were included at 25 kV for statistical purposes.)

Table 13

BACK SIDE COUPON TYPE D

Coupon	Breakdown kV	Leakage at Breakdown μA	kV at 1 μA Leakage
B-D-1	25*	2.3	17
B-D-2	25*	2.3	18
B-D-3	25*	2.3	14
B-D-4	25	10.0	10
B-D-5	25*	4.0	15
B-D-6	25*	5.5	15
B-D-9	22	12.5	10
B-D-10	22	7.0	11
B-D-11	21	7.0	6
B-D-12	24	7.9	9
B-D-13	24	14.2	8
B-D-14	25*	7.5	10
B-D-15	23	7.5	10
B-D-16	25*	10.5	9
B-D-17	25	13.0	9
B-D-18	24	15.0	7
B-D-19	22	5.5	10
B-D-20	25	8.0	11
B-D-21	25*	10.0	11
B-D-22	23	10.0	9
B-D-23	25	7.5	11
B-D-26	24	5.5	15
B-D-27	25*	7.5	10
B-D-28	25*	8.5	11
B-D-29	24	6.5	10
B-D-30	24	5.8	11

$n = 25$ $\bar{x} = 24$ kV $s_x = 1.2$

*No Breakdown (Samples with no breakdown were included at 25 kV for statical purposes.)

Table 14

SUMMARY OF ELECTRICAL TEST

Coupon	Type	Average Breakdown Voltage	Std. Dev.	High	Low
A	Front	15.6 kV	2.8	19	12
B	Front	15.2	1.9	19	12
C	Front	13.2	3.6	21	5
D	Front w/C.G.	18.1	3.7	22	10
D	Front no C.G.	15.8	4.0	25	12
A	Back	6.8	3.1	11	1
B	Back	8.6	2.1	13	5
C	Back	22.2	4.2	25	8
D	Back	24.0	1.2	25	21

Table 15

THERMAL ANALYSIS OF ROOF MOUNTED ARRAY

Module Type	Operating Condition	Power, W	T_{Cell}, °C	Power, W	T_{Cell}, °C
Wood*	Open Ckt	0	61.1	0	69.2
	Max Pwr	1.54	55.6	1.425	63.1
Steel**	Open Ckt	0	57.7	0	67.3
	Max Pwr	1.57	52.6	1.49	61.1

*Wood Substrate Data:

Front Cover: 3 mil Tedlar
Pottant: 10 mil EVA/Craneglas
Substrate: Wood, 200 mil thick
Back Cover: 10 mil white EVA
Cell: Single crystal silicon, AR coated (coating optimized for EVA/silicon interface)

**Steel Substrate Module Data:

Front Cover: 3 mil Tedlar
Pottant: 10 mil EVA/Craneglas
Substrate: Steel, 200 mil thick (no fins)
Back Cover: 10 mil white EVA
Cell: Single crystal silicon, AR coated (coating optimized for EVA/silicon interface)

Section 4.0

CONCLUSIONS AND RECOMMENDATIONS

There are no conclusions and recommendations for this period.

Section 5.0

PLANNED ACTIVITIES

During the next period verification testing will be completed. A design for the qualification modules will be finalized. The predicted versus measured values will be compared and the validity of the models assessed.